EXHIBIT 9

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Fabrication and performance of blue GaN-based vertical-cavity surface emitting laser employing AlN GaN and Ta 2 O 5 SiO 2 distributed Bragg reflector

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Fabrication and performance of blue GaN-based vertical-cavity surface emitting laser employing AlN/GaN and Ta_2O_5/SiO_2 distributed Bragg reflector

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GaN-based vertical-cavity surface emitting laser with 3 λ cavity and hybrid mirrors, consisting of the 25 pairs AlN/GaN dielectric Bragg reflector and the 8 pairs Ta_2O_5/SiO_2, was fabricated. The laser action was achieved under the optical pumping at room temperature with a threshold pumping energy density of about 53 mJ/cm^2. The laser emits 448 nm blue wavelength with a linewidth of 0.25 nm and the laser beam has a degree of polarization of about 84%. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2032598]

GaN-based materials have been attracting a great deal of attention due to the large direct band gap and the promising potential for the optoelectronic devices, including light emitting diodes and laser diodes.[1–4] Recently, much effort was devoted to the development of GaN-based vertical-cavity surface emitting laser (VCSEL).[5–8] The VCSEL possesses many advantageous properties over the edge emitting laser, including circular beam shape, light emission in vertical direction, and formation of two-dimensional arrays. In particular, the use of two-dimensional arrays of the blue VCSELs could reduce the readout time in high density optical storage and increase the scan speed in high-resolution laser printing technology.[9] The realization of the VCSEL requires a pair of high-reflectivity mirrors, usually in the form of dielectric Bragg reflectors (DBRs), for forming a high quality vertical cavity. Two types of the epitaxially grown high-reflectivity nitride mirrors were reported earlier using $GaN/Al_xGa_{1-x}N$ DBR with different aluminum content. Someya *et al.*[5] used 43 pairs of $Al_{0.34}Ga_{0.66}N/GaN$ as the bottom DBR and reported the lasing action at ~400 nm. Zhou *et al.*[8] employed a bottom DBR of 60 pairs $Al_{0.25}Ga_{0.75}N/GaN$ and observed the lasing action at 383.2 nm. All these AlGaN/GaN DBR structures required large numbers of pairs due to the relatively low refractive index contrast between $Al_xGa_{1-x}N$ and GaN. The DBR structure using AlN/GaN has higher refractive index contrast ($\Delta n/n=0.16$)[10] that can achieve high reflectivity with relatively less numbers of pairs. It also has wide stop band that can easily align with the active layer emission peak to achieve lasing action. Therefore, the AlN/GaN is attractive for application in nitride VCSEL. However, the AlN/GaN combination has relatively large lattice mismatch (~2.4%) and the difference in thermal expansion coefficients between GaN (5.59×10^{-6}/K) and AlN (4.2×10^{-6}/K) that tends to cause cracks in the epitaxial film during the growth of the AlN/GaN DBR structure could result in the reduction of reflectivity and increase in scattering loss. Recently, we have achieved high-reflectivity AlN/GaN DBR structure with a peak reflectance of 94% and a stop band about 18 nm with relatively smooth surface morphology.[11] Such AlN/GaN DBR with high reflectivity incorporated in the GaN vertical cavity light emitting device has shown to enhance the light emission intensity due to the resonant cavity effect.[12]

In this letter, we report the fabrication of GaN-based VCSEL using the AlN/GaN DBR as the bottom mirror and a Ta_2O_5/SiO_2 dielectric multiple layer structure as the top DBR mirror, and demonstration of the laser operation under optical pumping at room temperature.

The structure of the GaN-based VCSEL was grown in a vertical-type metalorganic chemical vapor deposition system (EMCORE D-75) with a fast rotating disk, which can hold one 2 in. wafer. The polished optical-grade C-face (0001) 2-in.-diam sapphire was used as substrate for the epitaxial growth of the VCSEL structure. Trimethylindium, trimethylgallium, trimethylaluminum, and ammonia were used as the In, Ga, Al, and N sources, respectively. Initially, a thermal cleaning process was carried out at 1080 °C for 10 min in a stream of hydrogen ambient before the growth of epitaxial layers. After depositing a 30-nm-thick GaN nucleation layer at 530 °C, the temperature was raised up to 1045 °C for the growth of a 1-μm-thick GaN buffer layer. Then a 25 pairs AlN/GaN DBR structure was grown at 1040 °C under the fixed chamber pressure of 100 Torr similar to the previous reported growth condition.[11,12] Then a 380-nm-thick *n*-type GaN, followed by a ten pair $In_{0.2}Ga_{0.8}N/GaN$ (2.5 nm/7.5 nm) multiple quantum well and a 100-nm-thick *p*-type GaN were grown to form a 3 λ cavity. Finally, an eight pair Ta_2O_5/SiO_2 dielectric mirror was deposited by the e gun as the top DBR reflector. The schematic diagram and the scanning electron microscopy (SEM) image of the overall VCSEL structure are shown in Figs. 1(a) and 1(b). During these processes, the reflectivity spectrum of the AlN/GaN DBR structure and the Ta_2O_5/SiO_2 dielectric mirror were measured by the *n&k* ultraviolet-visible spectrometer with

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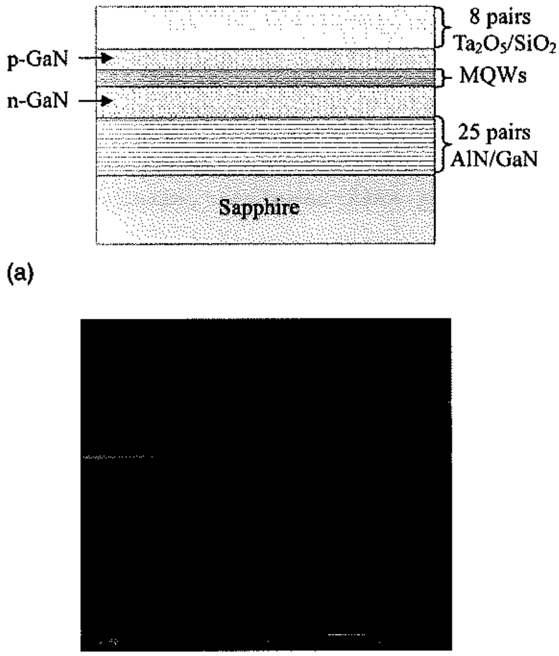

FIG. 1. (a) The schematic diagram of the overall vertical-cavity surface emitting laser structure. (b) The SEM image of the full structure.

normal incidence at room temperature. Figure 2 shows the reflectivity spectrum of AlN/GaN DBR and Ta_2O_5/SiO_2 DBR, respectively. The peak reflectance of the top and bottom DBR was 97.5% and 94% at 450 nm, respectively.

The emission spectrum of the GaN VCSEL structure was all measured using a microscopy system (WITec, alpha snom) at room temperature. The photoluminescence (PL) emission was excited by a 325 nm He–Cd laser with a spot size of about 10-μm-diameter. The optical pumping of the sample was performed using a frequency-tripled Nd:yittrium–vanadium–oxygen$_4$ 355 nm pulsed laser with a pulse width of ~0.5 ns at a repetition rate of 1 kHz. The pumping laser beam with a spot size of 60 μm was incident normal to the VCSEL sample surface. The light emission from the VCSEL sample was collected using an imaging optic into a spectrometer charge couple device (Jobin-Yvon

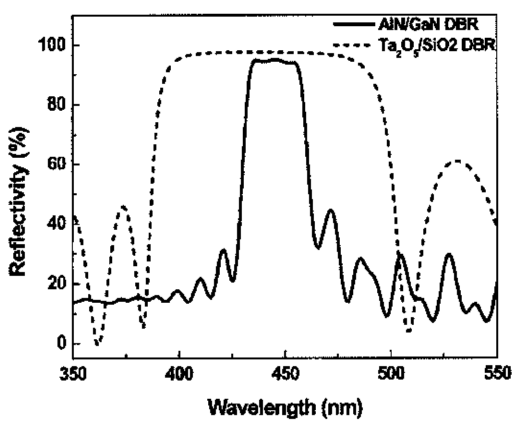

FIG. 2. The reflectivity spectrum of the top DBR(Ta_2O_5/SiO_2) and the bottom DBR(AlN/GaN): the peak reflectivity of the top DBR is about 97.5% and bottom DBR is about 94% at 450 nm, respectively.

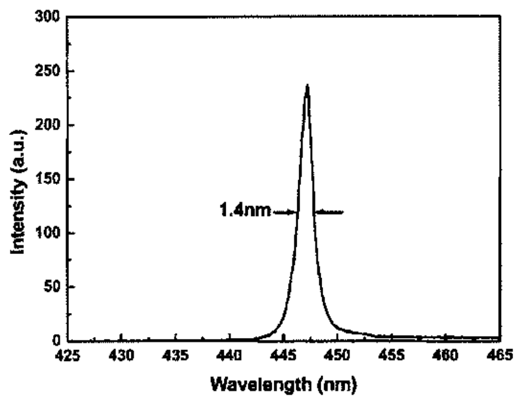

FIG. 3. The PL spectrum of the GaN-based VCSEL at room temperature.

Triax 320 Spectrometer) with a spectral resolution of ~0.1 nm for spectral output measurement.

Figure 3 shows the PL spectrum from the GaN-based VCSEL at room temperature. A narrow emission peak with full width at half maximum of 1.4 nm corresponding to the cavity resonant mode at 448 nm was observed. It indicates the emission peak was well aligned with vertical cavity formed by the high reflectance of AlN/GaN DBR and the Ta_2O_5/SiO_2 dielectric mirror. The cavity quality factor estimated from the emission linewidth of 1.4 nm is about 320. This value agrees with the VCSEL cavity formed by AlN/GaN DBR and Ta_2O_5/SiO_2 DBR.

The light emission intensity from the VCSEL as a function of the pumping energy is shown in Fig. 4. A distinct threshold characteristic was observed at the threshold pumping energy (E_{th}) of about 1.5 μJ corresponding to an energy density of 53 mJ/cm^2. Then the laser output increased linearly with the pumping energy beyond the threshold. The carrier density at the threshold is estimated to be about 3×10^{20} cm^{-3}, assuming the reflectivity of the top mirror at pumping wavelength of 355 nm was 40%, the absorption coefficient of the GaN was about 10^5 cm^{-1} at 355 nm[13] and the quantum efficiency was 10%.[5] We estimated the threshold gain (g_{th}) of our VCSEL cavity using the equation[5,6]

$$g_{th} \cong (1/2N_w L_w)\ln(1/R_1 R_2),$$

where N_w is the number of quantum wells, L_w is the width of each quantum well and R_1, R_2 are the reflectivity of the top and bottom mirrors, respectively. We obtained the required

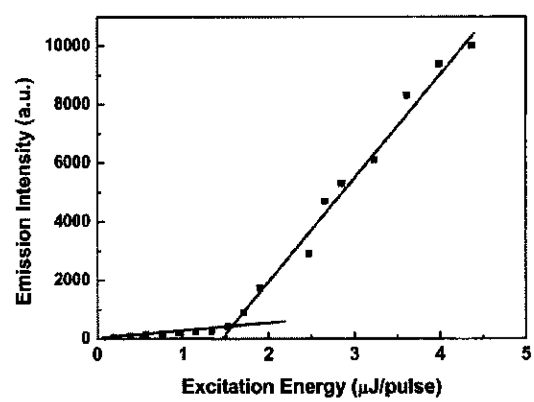

FIG. 4. The light output intensity as a function of the pumping energy at room temperature. The threshold energy was about 1.5 μJ.

TABLE I. The parameters used in the estimation of carrier density at threshold and threshold gain.

The reflectivity of the top mirror at 355 nm	40%
The absorption coefficient of the GaN at 355 nm	10^5 cm^{-1}[a]
The quantum efficiency	10%[b]
The number of quantum wells (N_w)	10
The width of each quantum well (L_w)	3 nm
The reflectivity of the top mirrors (R_1)	97.5%
The reflectivity of the bottom mirrors (R_2)	94.5%

[a]Reference 13.
[b]Reference 5.

threshold gain is about 1.45×10^4 cm^{-1}. The parameters used in the estimations of carrier density at threshold and threshold gain are listed in the Table I. The threshold gain value is roughly in agreement with the gain value estimated based on Nakamura's[14] report of the gain coefficient of InGaN at our threshold carrier density and slightly higher than the gain value of Park's report.[15]

Figure 5 shows the variation of emission spectrum with the increasing pumping energy. A dominant laser emission line at 448 nm appears above the threshold pumping energy. The laser emission spectral linewidth reduces with the pumping energy above the threshold energy and approaches 0.25 nm at the pumping energy of 2.52 E_{th}. The contrast of laser emission intensity between two orthogonal polarizations was measured by rotating a polarizer in front of the laser beam.

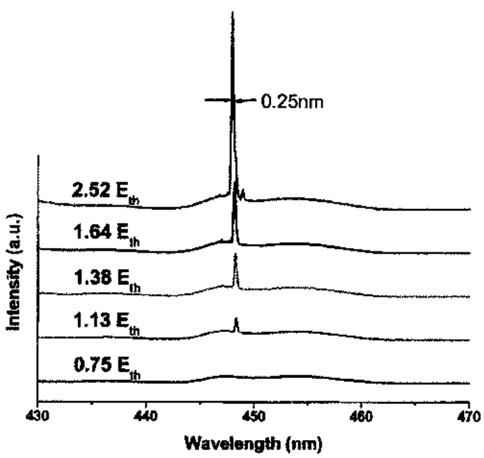

FIG. 5. The variation of laser emission spectrum with the increasing pumping energy. The laser emission wavelength is 448 nm with a linewidth of about 0.25 nm.

The variation of intensity with the angle of the polarizer shows nearly a cosine square variation. The degree of polarization (P) is defined as $P=(I_{max}-I_{min})/(I_{max}+I_{min})$, where I_{max} and I_{min} are the maximum and minimum intensity of the nearly cosine square variation, respectively. The result showed the laser beam has a degree of polarization of about 84% suggesting strong polarization property of the laser emission.

In conclusion, a GaN-based VCSEL with hybrid DBR mirrors, consisting of AlN/GaN DBR and Ta_2O_5/SiO_2 was fabricated. The laser action was achieved under the optical pumping at room temperature with a threshold pumping energy density of about 53 mJ/cm^2. The GaN VCSEL emits 448 nm blue wavelength with a linewidth of 0.25 nm and the laser beam shows a degree of polarization of about 84%.

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